Anomalous Hydrogen-Strontium Discharge

Randell L. Mills

Mark Nansteel

Ying Lu

BlackLight Power, Inc.

493 Old Trenton Road

Cranbury, NJ 08512

We report the observation of intense extreme ultraviolet (EUV) emission from incandescently heated atomic hydrogen and atomized strontium. Typically the emission of extreme ultraviolet light from hydrogen gas is achieved via a discharge at high voltage, a high power inductively coupled plasma, or a plasma created and heated to extreme temperatures by RF coupling (e.g. $> 10^6 \, K$) with confinement provided by a toroidal magnetic field. The observed plasma formed at low temperatures (e.g. $\approx 10^3 \, K$) from atomic hydrogen generated at a tungsten filament that heated a titanium dissociator and atomic strontium which was vaporized from the metal by heating. No emission was observed when sodium, magnesium, or barium replaced strontium or with hydrogen or strontium alone. The power balance of a gas cell having atomized hydrogen and strontium was measured by integrating the total light output corrected for spectrometer system response and energy over the visible range. Control cell experiments were identical except that sodium, magnesium, or barium replaced strontium. In the case of hydrogen-sodium, hydrogen-magnesium, and hydrogen-barium mixtures, 4000, 7000, and 6500 times the power of the hydrogen-strontium mixture was required, respectively, in order to achieve that same optically measured light output power. A plasma formed at a cell voltage of about 250 V for hydrogen alone and sodium-hydrogen mixtures, and 140-150 V for hydrogen-magnesium and hydrogen-barium mixtures; whereas, a plasma formed for hydrogen-strontium mixtures at an extremely low voltage of about 2 V.

I. INTRODUCTION

A historical motivation to cause EUV emission from a hydrogen gas was that the spectrum of hydrogen was first recorded from the only known source, the Sun [1]. Developed sources that provide a suitable intensity are high voltage discharge, synchrotron, and inductively coupled plasma generators [2]. An important variant of the later type of source is a tokomak [3]. Fujimoto et al. [4] have determined the cross section for production of excited hydrogen atoms from the emission cross sections for Lyman and Balmer lines when molecular hydrogen is dissociated into excited atoms by electron collisions. This data was used to develop a collisional-radiative model to be used in determining the ratio of molecular-to-atomic hydrogen densities in tokomak plasmas. Their results indicate an excitation threshold of 17 eV for Lyman α emission. Addition of other gases would be expected to decrease the intensity of hydrogen lines which could be absorbed by the gas. Hollander and Wertheimer [5] found that within a selected range of parameters of a plasma created in a microwave resonator cavity, a hydrogen-oxygen plasma displays an emission that resembles the absorption of molecular oxygen. Whereas, a helium-hydrogen plasma emits a very intense hydrogen Lyman α radiation at 121.5 nm which is up to 40 times more intense than other lines in the spectrum. The Lyman α emission intensity showed a significant deviation from that predicted by the model of Fujimoto et al. [4] and from the emission of hydrogen alone.

It has been reported that intense EUV emission was observed at low temperatures (e.g. $\approx 10^3 K$) from atomic hydrogen and certain atomized elements or certain gaseous ions which singly or multiply ionize at integer multiples of the potential energy of atomic hydrogen, $27.2 \, eV$ [6-10]. Helium ions present in the experiment of Hollander and Wertheimer [5] ionize at a multiple of two times the potential energy of atomic hydrogen.

Kuraica and Konjevic [11] observed intense wing developments of hydrogen Balmer lines with argon present in the plasma of negative glow of a glow discharge of an argon-hydrogen mixture irrespective of cathode material (carbon, copper, and silver). An anomalous discharge was not

2

observed in neon-hydrogen and pure hydrogen mixtures. The authors offer a tentative explanation for hydrogen line shapes in the presence of argon which is based on a quasiresonace charge transfer between metastable argon ions and hydrogen molecules and the formation of a hydrogen molecular ion. According to the authors,

"... it is essential that the H_2^+ or H_3^+ ion must gain energy in the electric field before dissociation. Otherwise, the large energy of excited hydrogen atoms (on the average 50 eV per atom) cannot be explained".

The source of $50\,eV$ anomalous thermal broadening of the Balmer lines observed by Kuraica and Konjevic [11] may be dependent on the presence of an atom or ion which ionizes at about an integer multiple of $27.2\,eV$ since Ar^+ ionizes at $27.6\,eV$.

Strontium ionizes at integer multiples of the potential energy of atomic hydrogen; thus, a hydrogen-strontium mixture was tested for anomalous EUV emission and plasma formation relative to mixtures of hydrogen and chemically similar controls that do not have electron ionization energies which are a multiple of $27.2\,eV$.

We report that a hydrogen plasma is formed at low temperatures (e.g. $\approx 10^3\,K$) by reaction of atomic hydrogen with strontium atoms, but not with magnesium, barium, or sodium atoms. In the case of EUV measurements, atomic hydrogen was generated by dissociation at a tungsten filament and at a transition metal dissociator that was incandescently heated by the filament. Strontium atoms were vaporized by heating to form a low vapor pressure (e.g. $1\,torr$). The kinetic energy of the thermal electrons at the experimental temperature of $\approx 10^3\,K$ were about 0.1 eV, and the average collisional energies of electrons accelerated by the field of the filament were less than 1 eV. (No blackbody emission was recorded for wavelengths shorter than $400\,nm$.). Strontium atoms caused hydrogen EUV emission; whereas, the chemically similar atoms, magnesium and barium as well as sodium, caused no emission.

Furthermore, an anomalous hydrogen-strontium discharge was observed by visible emission. A cylindrical nickel mesh hydrogen dissociator of a gas cell also served as an electrode to produce an

3

essentially uniform radial electric field between the dissociator and the wall of the cylindrical stainless steel gas cell. Power was applied to the electrode to achieve a bright plasma which was recorded over the wavelength range $350 \leq \lambda \leq 750\,nm$. The power balance of a gas cell having atomized hydrogen and strontium was measured by integrating the total light output corrected for spectrometer system response and energy over the visible range. Control experiments were identical except that sodium, magnesium, or barium replaced strontium. In the case of hydrogen-sodium, hydrogen-magnesium, and hydrogen-barium mixtures, 4000, 7000, and 6500 times the power of the hydrogen-strontium mixture was required, respectively, in order to achieve that same optically measured light output power.

II. EXPERIMENTAL

A. EUV spectroscopy

Due to the extremely short wavelength of this radiation, "transparent" optics do not exist for EUV spectroscopy. Therefore, a windowless arrangement was used wherein the source was connected to the same vacuum vessel as the grating and detectors of the EUV spectrometer. Windowless EUV spectroscopy was performed with an extreme ultraviolet spectrometer that was mated with the cell. Differential pumping permitted a high pressure in the cell as compared to that in the spectrometer. This was achieved by pumping on the cell outlet and pumping on the grating side of the collimator that served as a pin-hole inlet to the optics. The cell was operated under hydrogen flow conditions while maintaining a constant hydrogen pressure in the cell with a mass flow controller.

The experimental set up shown in Figure 1 comprised a quartz cell which was 500 mm in length and 50 mm in diameter. Three ports for gas inlet, outlet, and photon detection were on the other end of the cell. A tungsten filament (0.508 mm in diameter and 800 cm in length, total resistance ~2.5 ohm) and a titanium cylindrical screen (300 mm long and 40 mm in diameter) that performed as a hydrogen dissociator were inside the quartz cell. A new dissociator was used for each experiment.

The filament was coiled on a grooved ceramic tube support to maintain its shape when heated. The return lead passed through the inside of the ceramic tube. The titanium screen was electrically floated. The power was applied to the filament by a Sorensen 80-13 power supply which was controlled by a constant power controller. The temperature of the tungsten filament was estimated to be in the range of 1100 to 1500 °C. The external cell wall temperature was about 700 °C. The hydrogen gas pressure inside the cell was maintained at about 300 mtorr with a hydrogen flow rate of 5.5 sccm controlled by a 20 sccm range mass flow controller (MKS 1179A21CS1BB) with a readout (MKS type 246). The entire quartz cell was enclosed inside an insulation package comprised of Zircar AL-30 insulation. Several K type thermocouples were placed in the insulation to measure key temperatures of the cell and insulation. The thermocouples were read with a multichannel computer data acquisition system.

In the present study, the light emission phenomena was studied for hydrogen, argon, neon, and helium alone; hydrogen with strontium, magnesium, barium, and sodium metals, and strontium alone. The pure elements of magnesium, barium, and strontium were placed in the reservoir and volatized by the external heater. Magnesium, with a low vapor pressure (higher melting point), was volatilized by suspending a foil of the material (2 cm X 2 cm X 0.1 cm thick) between the filament and titanium dissociator and heating the test material with the filament. The power applied to the filament was 300 W in the case of strontium and up to 600 watts in the case of magnesium, barium, and sodium metals. The voltage across the filament was about 55 V and the current was about 5.5 ampere at 300 watts. For the controls, magnesium, barium, and sodium metals, the cell was increased in temperature to the maximum permissible with the power supply.

The light emission was introduced to an EUV spectrometer for spectral measurement. The spectrometer was a McPherson 0.2 meter monochromator (Model 302, Seya-Namioka type) equipped with a 1200 lines/mm holographic grating with a platinum coating. The wavelength region covered by the monochromator was $30-560\,nm$. A channel electron multiplier (CEM) was used to detect the EUV light. The wavelength resolution was about $1\,nm$ (FWHM) with an entrance and exit

slit width of 300 μm. The vacuum inside the monochromator was maintained below 5×10^{-4} torr by a turbo pump. The EUV spectrum ($40-160$ nm) of the cell emission with strontium present was recorded at about the point of the maximum Lyman α emission.

The UV/VIS spectrum ($40-560$ nm) of the cell emission with hydrogen alone was recorded with a photomultiplier tube (PMT) and a sodium salicylate scintillator. The PMT (Model R1527P, Hamamatsu) used has a spectral response in the range of $185-680$ nm with a peak efficiency at about 400 nm. The scan interval was 0.4 nm. The inlet and outlet slit were 500 μm with a corresponding wavelength resolution of 2 nm.

B. Power cell apparatus and procedure

Plasma studies with hydrogen alone, or hydrogen with strontium, sodium, magnesium, or barium were carried out in the cylindrical stainless steel gas cell shown in Fig. 2. The experimental setup for generating a glow discharge hydrogen plasma and for optically measuring the power balance is shown in Fig. 3. The cell was heated in a 10 kW refractory brick kiln (L & L Kiln Model JD230) as shown in Fig. 3. The cell was evacuated and pressurized with hydrogen through a single 0.95 cm feed through. The discharge was started and maintained by an alternating current electric field in the 1.75 cm annular gap between an axial electrode and the cell wall. The cylindrical cell was 9.21 cm in diameter and 14.5 cm in height. The axial electrode was a 5.08 cm OD by 7.2 cm long stainless steel tube wound with several layers of nickel screen. The overall diameter of the axial electrode was 5.72 cm. A 1.6 mm thick UV-grade sapphire window with 1.5 cm view diameter provided a visible light path from inside the cell. The viewing direction was normal to the cell axis. A 1.27 cm diameter stainless steel tube passed through the furnace wall and connected to a view port welded to the cell wall at mid-height to provide an optical light path from the sapphire window to the furnace exterior. An 8 mm quartz rod channeled the light from the view port through the stainless tube to a collimating lens which was focused on a 100 μm optical fiber located outside the furnace. Spectral data was recorded with a visible spectrometer (Ocean

Optics S2000) and stored by a personal computer.

The field voltage was controlled by a variable voltage transformer operating from 115 VAC, 60 Hz. A step-up transformer was used when necessary. True rms voltage at the axial electrode was monitored by a digital multimeter (Fluke 8010 A or Tenma 726202). A second multimeter (Extech 380763) in series with the discharge gap was used to indicate the current. The cell temperature was measured by a thermocouple probe located in the cell interior approximately 2 cm from the discharge gap. The pressure in the hydrogen supply tube outside the furnace was monitored by 10 torr and 1000 torr MKS Baratron absolute pressure gauges. In the absence of hydrogen flow, the hydrogen supply tube pressure was essentially the cell hydrogen partial pressure.

Strontium (Aldrich Chemical Company 99.9 %), sodium (Aldrich Chemical Company 99.95 %), magnesium (Alfa Aesar 99.98 %), or barium (Aldrich Chemical Company 99.99 %) metals were loaded into the cell under a dry argon atmosphere. The cell was evacuated with a turbo vacuum pump to a pressure of 4 mtorr during most of the heating process. During the heat-up the cell was periodically pressurized with hydrogen (99.999% purity) to approximately 100 torr and subsequently evacuated to purge gaseous contaminants from the system. When the cell temperature stabilized hydrogen was added until the steady pressure was approximately 1 torr. The field voltage was increased until breakdown occurred. This was confirmed by the spectrometer response to visible light emitted from the cell. The hydrogen pressure was adjusted, as much as possible, to maximize the light emission from the cell. The voltage was maintained at the minimum level which resulted in a stable discharge during data acquisition.

The spectrometer system comprised a 100 μm optical fiber and visible spectrometer (Ocean Optics S2000). To correct for the nonuniform response of the spectrometer system as a function of wavelength and the dependence of energy on wavelength, the system was calibrated against a reference light source (Ocean Optics LS-1-CAL). A spectral calibration factor was applied to the count rate data at each wavelength to yield the irradiation of the detector in units of energy/time/area/wavelength. The total visible radiant flux incident on the detector was calculated by integrating the spectral irradiation between 400 and 700 nm.

III. RESULTS

A. EUV spectroscopy

The cell without any test material present was run to establish the baseline of the spectrometer. The intensity of the Lyman α emission as a function of time from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, and 300 mtorr hydrogen with a flow rate of 5.5 sccm is shown in Fig. 4. The corresponding UV/VIS spectrum ($40-560\,nm$) is shown in Fig. 5. The spectrum was recorded with a photomultiplier tube (PMT) and a sodium salicylate scintillator. No emission was observed except for the blackbody filament radiation at the longer wavelengths. No emission was also observed when argon, neon, or helium replaced hydrogen.

The intensity of the Lyman α emission as a function of time from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, sodium or barium metal in the catalyst reservoir, and 300 mtorr hydrogen with a flow rate of 5.5 sccm are shown in Figs. 6 and 7, respectively. Sodium or barium metal was volatized from the catalyst reservoir by heating it with an external heater. No emission was observed in either case. The maximum filament power was greater than 500 watts. A metal coating formed in the cap of the cell over the course of the experiment in both cases.

The intensity of the Lyman α emission as a function of time from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, a magnesium foil in the cell versus strontium metal in the catalyst reservoir, and 300 mtorr hydrogen with a flow rate of 5.5 sccm are shown in Figs. 8 and 9, respectively. No emission was observed with the magnesium foil and hydrogen. The maximum filament power was 500 watts. The temperature of the foil increased with filament power. At 500 watts, the temperature of the foil was 1000 °C which would correspond to a vapor pressure of about 100 mtorr. Strontium metal was volatized from the catalyst reservoir by heating it with an external heater. Strong emission was observed from strontium and hydrogen. The EUV spectrum ($40-160\,nm$) of the cell

emission recorded at about the point of the maximum Lyman α emission is shown in Fig. 10. No emission was observed in the absence of hydrogen flow. A metal coating formed in the cap of the cell over the course of the experiment in the case of magnesium and strontium.

B. Optically measured power balance

Count rate and spectrometer system irradiation of the background spectrum of hydrogen and strontium vapor over the wavelength range $350 \le \lambda \le 750\ nm$ in the absence of power applied to the electrode and in the absence of a discharge is shown in Fig. 11. This data was collected during cell evacuation following the test with strontium and hydrogen at a cell temperature of 664 °C. The maximum visible irradiation of $0.004\ \mu W/cm^2 nm$ occurred at the red end of the visible spectrum. The results are summarized in Table I where T is the temperature, P_{hyd} is the hydrogen partial pressure, and P_v is the equilibrium metal vapor pressure calculated from standard curves of the vapor pressure as a function of temperature [12].

Power was applied to the electrode to achieve a bright plasma in the strontium-hydrogen mixture and the controls of hydrogen alone, and sodium-hydrogen, magnesium-hydrogen, and barium-hydrogen mixtures for cell temperatures in the range 335-666 °C. In each case, the spectral radiant flux at the spectrometer system was recorded. If possible, the power driving the controls was adjusted such that the peak spectrometer system spectral irradiation was about $0.1\ \mu W/cm^2 nm$ in each case. The integrated visible irradiation levels were of the order of $1\ \mu W/cm^2$. One exception was the case of hydrogen-barium. In this case, the maximum spectral irradiation levels and integrated visible irradiation levels were only of the order of $0.01\ \mu W/cm^2 nm$ and $0.03\ \mu W/cm^2$, respectively.

The power required to maintain a plasma of equivalent optical brightness with strontium atoms present was 4000, 7000, and 6500 times less than that required for the sodium, magnesium, and barium control, respectively. A driving power of 33.7 W and 58 W was necessary to achieve a total visible radiant flux of about $1\ \mu W/cm^2$ from a sodium-hydrogen mixture and a magnesium-hydrogen mixture, respectively. For a hydrogen-barium mixture, a power input of about 55

9

W was required to achieve a total visible irradiation of about $0.03 \, \mu W/cm^2$. Whereas, in the case of a strontium-hydrogen mixture, a power input of 8.5 mW resulted in a plasma with a total visible radiant flux of about the same optical brightness as sodium and magnesium. A plasma formed at a cell voltage of about 250 V for hydrogen alone and sodium-hydrogen mixtures, and 140-150 V for hydrogen-magnesium and hydrogen-barium mixtures; whereas, a plasma formed for hydrogen-strontium mixtures at the extremely low voltage of about 2 V. The results are summarized in Table I.

The count rate and the spectrometer system irradiation for a mixture of hydrogen and strontium vapor at 664 °C is shown in Fig. 12. Optimal light emission was observed after several hours of cell evacuation. The hydrogen partial pressure was unknown under these conditions. The calculated equilibrium vapor pressure of strontium at 664 °C is approximately 270 mtorr. The measured breakdown voltage was approximately 2 V. The maintenance voltage for a stable discharge was 2.2 V and input power was 8.5 mW. Spectral characteristics are noted in Table II. The hydrogen Balmer α and β peaks were obscured by strong strontium emission near 654.7 and 487.2 nm, respectively.

The spectrometer system irradiation for a hydrogen discharge at a cell temperature of 664 °C and 1 torr is shown in Fig. 13. The breakdown voltage was approximately 220 V. The field voltage required to form a stable discharge was 224 V. The input power was 24.6 W. Spectral features are tabulated in Table III. The peak at 589.1 nm may be due to sodium contamination from a previous experimental run. The minor peaks at 518.2 and 558.7 nm have not been identified.

The spectrometer system irradiation for mixtures of hydrogen and sodium vapor are shown in Figs. 14-16 for temperatures of 335, 516, and 664 °C, respectively. Corresponding hydrogen pressures are 1, 1.5, and 1.5 torr, respectively. The calculated sodium vapor pressure was 51 mtorr, 5.3 torr, and 63 torr at 335, 516, and 664 °C, respectively. At least 200 V was required to maintain a discharge. The input power for a stable discharge ranged from approximately 10 W at 664 °C to 34 W at 335 °C. Spectral features corresponding to 335 °C are summarized in Table IV. Strong emission observed near 656-657 nm was probably due, in-part, to hydrogen. The relative contribution to the intensity was

masked by strong sodium emission at a slightly shorter wavelength. The peak at 486.2 nm could only be due to hydrogen emission. Sodium does not have emission lines in the neighborhood of this wavelength. The intensity of this peak diminishes relative to the more prominent sodium peaks with increasing temperature as shown in Figs. 14-16. This may have been due to a decreasing hydrogen concentration as the sodium vapor pressure increased.

The spectral response for mixtures of magnesium vapor and hydrogen are shown in Figs. 17-19 for temperatures of 449, 582, and 654 °C, respectively. The corresponding hydrogen pressures are 4, 4.2, and 3 torr, respectively. A minimum of 150 V was required to maintain a discharge. The minimum input power required to maintain a stable discharge was 58 W at 449 °C. Spectral features corresponding to 449 °C are summarized in Table V. Both hydrogen and magnesium spectral features are observed. The modest sodium emission at 588 nm may be due to sodium contamination from previous control experiments.

The spectral response for a mixture of barium vapor and hydrogen at 666°C is shown in Fig. 20. The hydrogen partial pressure and barium vapor pressure are 2 torr and 25 mtorr, respectively. It was not possible to achieve a total visible irradiation level of $1\,\mu W/cm^2$ even with voltages approaching 150 V. The voltage and power input corresponding to Fig. 20 are 138 V and 55 W, respectively. Spectral features are summarized in Table VI. Both barium and hydrogen spectral features are observed as well as sodium features which are presumably due to contamination. The peak at 493 nm has not been identified.

IV. DISCUSSION

Intense EUV emission was observed at low temperatures (e.g. $\approx 10^3\,K$) from atomic hydrogen and strontium which ionizes at integer multiples of the potential energy of atomic hydrogen. In the cases where Lyman α emission was observed, no possible chemical reactions of the tungsten filament, the dissociator, the vaporized test material, and 300 mtorr hydrogen at a cell temperature of 700 °C could be found which accounted for the hydrogen α line emission. In fact, no known chemical reaction releases enough energy to excite Lyman α emission from

11

hydrogen. The emission was not observed with hydrogen alone or with helium, neon, or argon gas. Intense emission was observed for strontium with hydrogen gas, but no emission was observed with hydrogen or strontium alone. This result indicates that the emission may be due to a reaction of hydrogen.

Other studies support the possibility of a novel reaction of atomic hydrogen which produces an anomalous discharge. It has been previously reported that intense extreme ultraviolet (EUV) emission was observed at low temperatures (e.g. $\approx 10^3\,K$) from atomic hydrogen and certain atomized elements or certain gaseous ions [6-10]. The only pure elements that were observed to emit EUV were those wherein the ionization of t electrons from an atom to a continuum energy level is such that the sum of the ionization energies of the t electrons is approximately $m \cdot 27.2\,eV$ where t and m are each an integer. Strontium atoms ionize at integer multiples of the potential energy of atomic hydrogen and caused emission. Whereas, the chemically similar atoms, magnesium and barium as well as sodium, do not ionize at integer multiples of the potential energy of atomic hydrogen and caused no emission. The enthalpy of ionization of Sr to Sr^{5+} has a net enthalpy of reaction of $188.2\,eV$, which is equivalent to $m = 7$.

The power balance of a gas cell having atomized hydrogen and strontium was measured by integrating the total light output corrected for spectrometer system response and energy over the visible range. A control cell was identical except that sodium, magnesium, or barium replaced strontium. In the controls, 4000-7000 times the power of the strontium cell was required in order to achieve the same optically measured light output power. A plasma formed at a cell voltage of about 250 V for hydrogen alone and sodium-hydrogen mixtures, and 140-150 V for hydrogen-magnesium and hydrogen-barium mixtures; whereas, a plasma formed for hydrogen-strontium mixtures at the extremely low voltage of about 2 V. This is two orders of magnitude lower than the starting voltages measured for gas glow discharges, cf. Table VII.

An anomalous plasma with hydrogen-potassium mixtures has been reported in an experiment identical to the present EUV experiments [9-10]. When the electric field was set to zero, the plasma decayed with a two second half-life which was the thermal decay time of the filament

which dissociated molecular hydrogen to atomic hydrogen. This experiment showed that hydrogen line emission was occurring even though the voltage between the heater wires was set to and measured to be zero and indicated that the emission was due to a reaction of potassium atoms with atomic hydrogen. Potassium atoms ionize at an integer multiple of the potential energy of atomic hydrogen, $m \cdot 27.2 \, eV$. The enthalpy of ionization of K to K^{3+} has a net enthalpy of reaction of $81.7426 \, eV$, which is equivalent to $m = 3$.

In the present experiments, it was determined that the presence of a weak electric field was necessary in order for strontium to produce an anomalous discharge of hydrogen. In the case that electrons are ionized to a continuum energy level, the presence of a low strength electric field alters the continuum energy levels. The minimum electric field in this experiment was about 2 V over the annular gap of about 2 cm. The ionization energy of $188.2 \, eV$ is 1% less than $m \cdot 27.2 \, eV$ where $m = 7$. In the anomalous discharge of hydrogen due to the presence of strontium, the weak field may adjust the energy of ionizing strontium to match the energy of $m \cdot 27.2 \, eV$ to permit a novel reaction of atomic hydrogen.

The formation of novel compounds would be substantial evidence supporting a novel reaction of hydrogen as the mechanism of the observed EUV emission and anomalous discharge. Novel hydrogen compounds have been isolated as products of the reaction of atomic hydrogen with atoms and ions identified as catalysts in the present EUV study [6-10, 16-21].

ACKNOWLEDGMENT

REFERENCES
1. Phillips, J. H., *Guide to the Sun*, Cambridge University Press, Cambridge, Great Britain, (1992), pp. 16-20.
2. J. A. R. Sampson, *Techniques of Vacuum Ultraviolet Spectroscopy*, Pied

Publications, (1980), pp. 94-179.

3. Science News, 12/6/97, p. 366.

4. T. Fujimoto, K. Sawada, and K. Takahata, J. Appl. Phys., Vol. 66 (6), (1989), pp. 2315-2319.

5. A. Hollander, and M. R. Wertheimer, J. Vac. Sci. Technol. A, Vol. 12 (3), (1994), pp. 879-882.

6. R. Mills, J. Dong, Y. Lu, "Observation of Extreme Ultraviolet Hydrogen Emission from Incandescently Heated Hydrogen Gas with Certain Catalysts", 1999 Pacific Conference on Chemistry and Spectroscopy and the 35th ACS Western Regional Meeting, Ontario Convention Center, California, (October 6-8, 1999).

7. R. Mills, J. Dong, Y. Lu, "Observation of Extreme Ultraviolet Hydrogen Emission from Incandescently Heated Hydrogen Gas with Certain Catalysts", Int. J. Hydrogen Energy, Vol. 25, (2000), pp. 919-943.

8. R. Mills, "Observation of Extreme Ultraviolet Emission from Hydrogen-KI Plasmas Produced by a Hollow Cathode Discharge", Int. J. Hydrogen Energy, in press.

9. R. Mills, "Temporal Behavior of Light-Emission in the Visible Spectral Range from a Ti-K2CO3-H-Cell", Int. J. Hydrogen Energy, in press.

10. R. Mills, M. Nansteel, and Y. Lu, "Observation of Extreme Ultraviolet Hydrogen Emission from Incandescently Heated Hydrogen Gas with Strontium that Produced an Anomalous Optically Measured Power Balance", Int. J. Hydrogen Energy, in press.

11. Kuraica, M., Konjevic, N., Physical Review A, Volume 46, No. 7, October (1992), pp. 4429-4432.

12. C. L. Yaws, *Chemical Properties Handbook*, McGraw-Hill, (1999).

13. David R. Linde, *CRC Handbook of Chemistry and Physics*, 79 th Edition, CRC Press, Boca Raton, Florida, (1998-9), pp. 10-1 to p. 10-87.

14. A. von Engel, *Ionized Gases*, American Institute of Physics, (1965).

15. M. S. Naidu and V. Kamaraju, *High Voltage Engineering*, McGraw-Hill, (1996).

16. R. Mills, B. Dhandapani, N. Greenig, J. He, "Synthesis and Characterization of Potassium Iodo Hydride", Int. J. of Hydrogen Energy, Vol. 25, Issue 12, December, (2000), pp. 1185-1203.

17. R. Mills, "Novel Inorganic Hydride", Int. J. of Hydrogen Energy, Vol. 25, (2000), pp. 669-683.

18. R. Mills, "Novel Hydrogen Compounds from a Potassium Carbonate Electrolytic Cell", Fusion Technology, Vol. 37, No. 2, March, (2000), pp. 157-182.

19. R. Mills, J. He, and B. Dhandapani, "Novel Hydrogen Compounds", 1999 Pacific Conference on Chemistry and Spectroscopy and the 35th ACS Western Regional Meeting, Ontario Convention Center, California, (October 6-8, 1999).

20. R. Mills, B. Dhandapani, M. Nansteel, J. He, T. Shannon, A. Echezuria, "Synthesis and Characterization of Novel Hydride Compounds", Int. J. of Hydrogen Energy, in press.

21. R. Mills, "Highly Stable Novel Inorganic Hydrides", Journal of Materials Research, submitted.

Table I. Discharge conditions and comparison of the driving power to achieve a total visible radiant flux of about 1 $\mu W/cm^2$.

	T (°C)	$P_{hyd.}$ (torr)[a]	P_v (Torr)	Voltage (V)	Current (mA)	Integ. time (ms)	Detector irradiation ($\mu W/cm^2$)	Power (W)
H_2+Sr	664	- - - -	0.270	2.20	3.86	768	1.17	0.0085
H_2	664	1.0	- - - -	224	110	1130	2.08	24.6
H_2+Na	335	1.0	0.051	272	124	122	1.85	33.7
H_2+Na	516	1.5	5.3	220	68	768	0.40	15.0
H_2+Na	664	1.5	63	240	41	768	0.41	9.84
H_2+Mg	449	4.0	0.016	153	380	500	1.7	58
H_2+Mg	582	4.2	0.6	233	290	500	0.16	68
H_2+Mg	654	3.0	2.8	250	400	1000	0.18	100.0
H_2+Ba	666	2.0	0.025	138	730	716	0.03	55[b]
Bkgnd.	664	- - - -	0.270	0	0	768	0.20	0

[a] Calculated [12]

[b] Power input differs from volt-amperes due to non-unity power factor.

TABLE II. Spectral features of hydrogen and strontium at 664 °C.

Measured Wavelength (nm)	Spectrometer System Irradiation $\left(\mu W/cm^2 nm\right)$	Published Emission Data [13] (nm)
460.6	0.156	460.73 (Sr)
487.2	0.00290	487.25 (Sr), 486.13 (H_2)
639.8	0.00813	638.82 (Sr)
654.7	0.0139	654.68 (Sr), 656.29 (H_2)
689.4	0.0386	689.26 (Sr)

TABLE III. Spectral features of hydrogen at 664 °C.

Measured Wavelength (nm)	Spectrometer System Irradiation $(\mu W/cm^2 nm)$	Published Emission Data [13] (nm)
485.8	0.0165	486.13 (H_2)
518.2	0.00894	
558.7	0.00694	
589.1	0.0174	589.00 (Na), 589.59 (Na)
656.7	0.0752	656.29 (H_2)

TABLE IV. Spectral features of hydrogen and sodium at 335 °C.

Measured wavelength (nm)	Spectrometer System Irradiation $(\mu W/cm^2 nm)$	Published emission data [13] (nm)
467.2	0.00400	466.86 (Na)
486.2	0.0055	486.13 (H_2)
498.4	0.0176	498.28 (Na)
516.1	0.00380	515.34 (Na)
569.0	0.114	568.82 (Na)
589.3	0.302	589.00 (Na), 589.59 (Na)
615.9	0.0310	616.07 (Na)
656.0	0.0422	656.29 (H_2), 655.24 (Na)
657.0	0.0421	656.29 (H_2)

TABLE V. Spectral features of hydrogen and magnesium at 449 °C.

Measured wavelength (*nm*)	Spectrometer system irradiation $\left(\mu W/cm^2 nm\right)$	Published emission data [13] (*nm*)
382.6	0.0843	382.93 (Mg), 383.23 (Mg)
384.0	0.0643	383.83 (Mg)
485.2	0.0122	486.13 (H_2)
517.3	0.0353	517.27 (Mg), 518.36 (Mg)
588.1	0.0167	589.00 (Na), 589.59 (Na)
655.8	0.109	656.29 (H_2)

Table VI. Spectral features of hydrogen and barium at 666°C.

Measured wavelength (nm)	Spectrometer system irradiation (mW/cm^2-nm)	Published emission data [13] (nm)
456.2	0.0021	455.40 (Ba)
492.6	0.002	
552.7	8.4×10^{-4}	553.55 (Ba)
568.4	0.003	568.26 (Na)
588.8	0.006	589.00 (Na)
614.7	9.0×10^{-4}	614.17 (Ba)
655.9	0.002	656.29 (H_2)

TABLE VII. Glow discharge parameters from von Engel [14] and Naidu Kamaraju [15].

Gas	Minimum starting voltage (V)	Pressure-discharge gap product at minimum starting voltage (cm-torr)
N_2	251	0.67
H_2	273	1.15
Air	327	0.567
CO_2	420	0.51
Ar	137	0.9
He	156	4.0
Hg	520	2
Na	335	0.04

Figure Captions

FIG. 1. The experimental set up comprising a' gas cell light source and an EUV spectrometer which was differentially pumped.

FIG. 2. Cylindrical stainless steel gas cell for plasma studies with hydrogen alone, or with hydrogen with strontium, sodium, or magnesium.

FIG. 3. The experimental setup for generating a glow discharge hydrogen plasma and for optically measuring the power balance.

FIG. 4. The intensity of the Lyman α emission as a function of time from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, and 300 mtorr hydrogen with a flow rate of 5.5 sccm.

FIG. 5. The UV/VIS spectrum (40 – 560 nm) of the cell emission from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, and 300 mtorr hydrogen with a flow rate of 5.5 sccm that was recorded with a photomultiplier tube (PMT) and a sodium salicylate scintillator.

FIG. 6. The intensity of the Lyman α emission as a function of time from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, sodium metal vaporized from the catalyst reservoir, and 300 mtorr hydrogen with a flow rate of 5.5 sccm.

FIG. 7. The intensity of the Lyman α emission as a function of time from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, barium metal vaporized from the catalyst reservoir, and 300 mtorr hydrogen with a flow rate of 5.5 sccm.

FIG. 8. The intensity of the Lyman α emission as a function of time from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, a magnesium foil, and 300 mtorr hydrogen with a flow rate of 5.5 sccm.

FIG. 9. The intensity of the Lyman α emission as a function of time from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, strontium metal vaporized from the catalyst reservoir, and 300 mtorr hydrogen with a flow rate of 5.5 sccm.

FIG. 10. The EUV spectrum (40 – 160 nm) of the cell emission recorded at about the point of the maximum Lyman α emission from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a

titanium dissociator, strontium metal vaporized from the catalyst reservoir, and 300 mtorr hydrogen with a flow rate of 5.5 sccm.

FIG. 11. Count rate and spectrometer system irradiation of the background spectrum of hydrogen and strontium vapor over the wavelength range $350 \leq \lambda \leq 750\,nm$ in the absence of power applied to the electrode and in the absence of a discharge.

FIG. 12. The count rate and the spectrometer system irradiation for a mixture of hydrogen and strontium vapor at 664 °C.

FIG. 13. The spectrometer system irradiation for a hydrogen discharge at a cell temperature of 664 °C and a hydrogen pressure of 1 torr.

FIG. 14. The spectrometer system irradiation for a mixture of hydrogen and sodium vapor at 335 °C.

FIG. 15. The spectrometer system irradiation for a mixture of hydrogen and sodium vapor at 516 °C.

FIG. 16. The spectrometer system irradiation for a mixture of hydrogen and sodium vapor at 664 °C.

FIG. 17. The spectrometer system irradiation for a mixture of hydrogen and magnesium vapor at 449 °C.

FIG. 18. The spectrometer system irradiation for a mixture of hydrogen and magnesium vapor at 582 °C.

FIG. 19. The spectrometer system irradiation for a mixture of hydrogen and magnesium vapor at 654 °C.

Fig. 20. The spectrometer system irradiation for a mixture of hydrogen and barium vapor at 666 °C.

Grating

Turbo pump

VUV Spectrometer

Collimator

Gas inlet

Light

Exit slit

Photon Detector
CEM or PMT

Entrance slit

Pump

Quartz cell

Tungston coil heater

Titanium mesh screen

Sample reservoir

Fig. 1 Mills
Phys Rev A

Fig. 2
Miles
Phys. Rev. A

Thermowell

Cell
9.21 cm x 14.5 cm

Gas fill/vacuum

Thermowell

Nickel
electrode

High voltage
feed-through

Axial electrode
5.72 cm x 7.2 cm

Nickel
screen

Sapphire
viewport
1.5 cm

Stainless
tube
1.27 cm

Furnace
wall

Quartz rod
8 mm

Collimating
lens

Optical fiber
100 micron

Fig. 3
mills
phys Rev A

Hydrogen gas only

Wavelength=121.57 nm

Photon Counts/sec

Time (min)

Fig. 4
mills
phys Rev A

Hydrogen gas only

Photon Counts/sec

Wavelength (nm)

Fig. 5
milli
phys Part A

Na

Wavelength=121.57 nm

Time (min)

Photon Counts/sec

Fig. 6
Miiis anr A
phys

Ba metal
Wavelength=121.57 nm

Photon Counts

Time (Min)

Fig. 7
Mills
Phys Rev A

Mg

Wavelength=121.57 nm

Photon Counts/sec

Time (min)

Fig. 8
Mills
Phenomena

Sr

Wavelength=121.57 nm

Photon Counts/sec

Time (min)

Fig. 9
phys/vARUA

Fig. 10
Prior Art

Fig. 12
Mills
Phys Rev A

Fig. 12

Axis labels: Count Rate (cts/s) — 0, 1000, 2000, 3000, 4000, 5000; Detector Irradiation (microwatt/sq. cm-nm) — 0, 0.04, 0.08, 0.12, 0.16, 0.2; Wavelength (nm) — 350, 400, 450, 500, 550, 600, 650, 700, 750. Annotations: "Detector irradiation" and "Count rate".

Fig. 13
Millie
phys A z r A

Fig. 14
Milli
phos Arc A
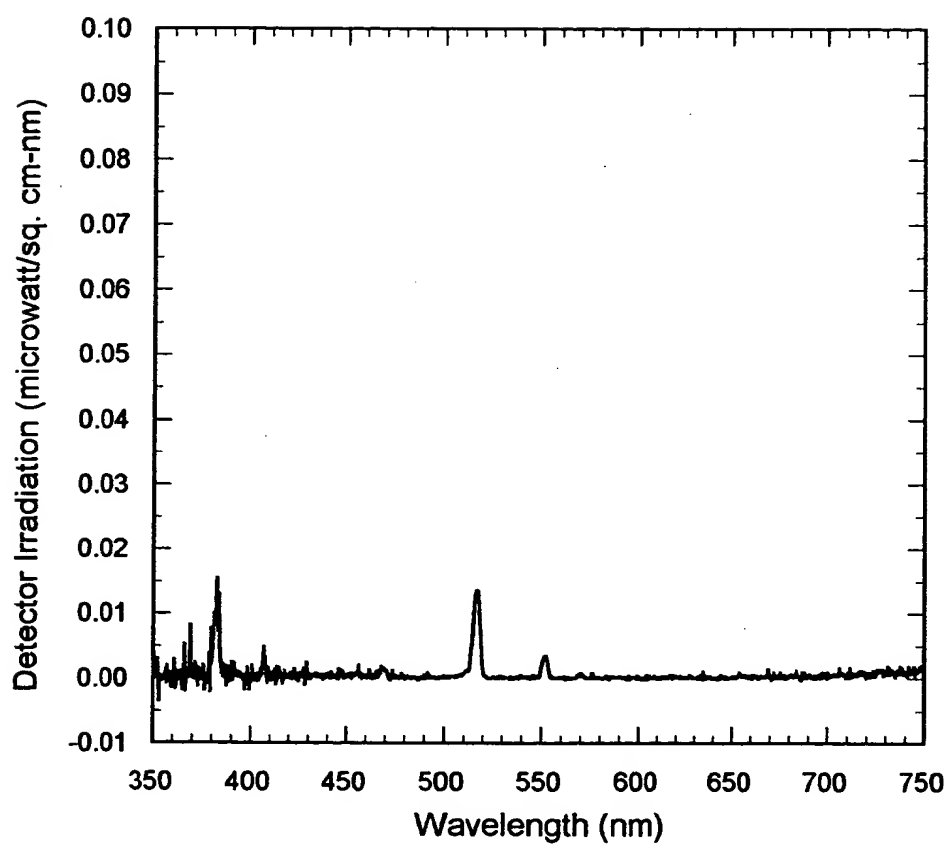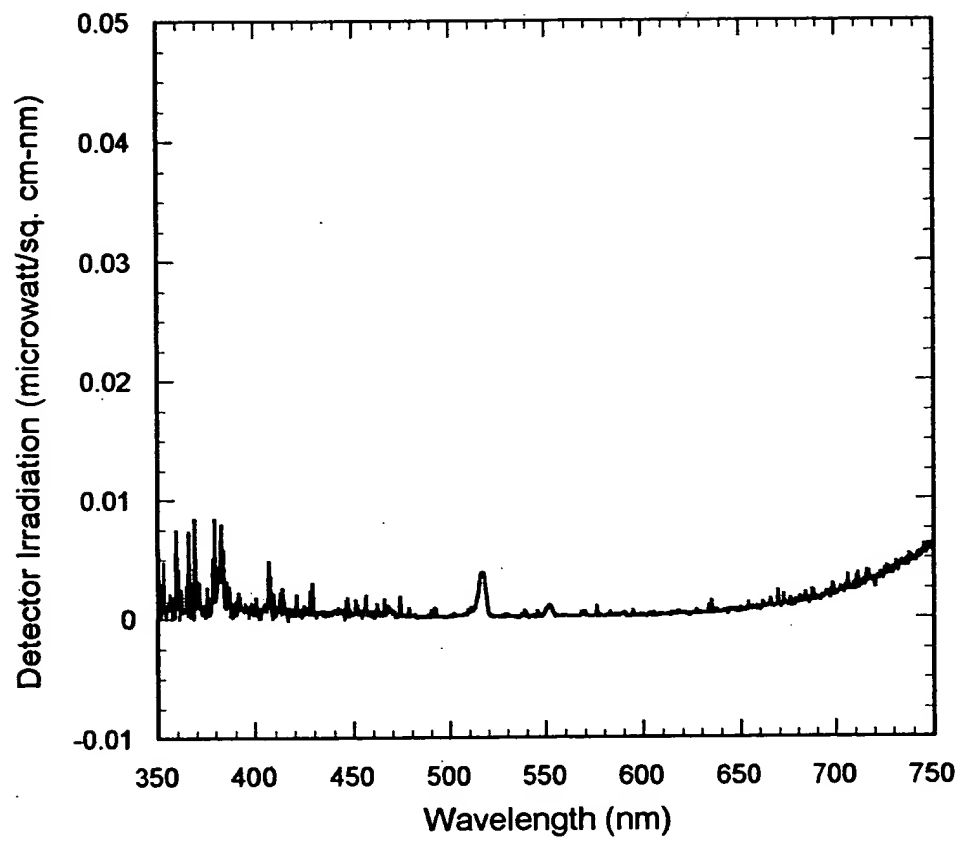
Fig. 16
Mills
Phys Rev A

Fig. 17
Mills
phys Rev A

Fig. 18
Miller
phys Rev A

Fig. 19
M. Ili,
Phys. Rev A

Fig. 20
Mills
phys. Rev A.